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van der Schoot, M.; Smulders, F.T.Y.; Los, S.A.; Kok, A

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EFFECTS OF MIXED VERSUS BLOCKED DESIGN ON STIMULUS EVALUATION: COMBINING UNDERADDITIVE EFFECTS [1,2]

MENNO VAN DER SCHOOT

Vrije Universiteit Amsterdam

FREN T. Y. SMULDERS

Maastricht University

SANDER A. LOS

Vrije Universiteit Amsterdam

ALBERT KOK

University of Amsterdam

Summary.—According to the asynchronous discrete coding model of Miller, two manipulations should display underadditive effects on reaction time if they slow down noncontingent stages associated with the processing of two separable dimensions of a stimulus. Underadditive effects are also predicted by a dual route model when a task variable is factorially varied with design type (mixed vs blocked). Interpretations of both underadditive effects and their combination were evaluated. Intact and degraded stimuli were presented to 18 young adults either in a single block (mixed) or in separate blocks (blocked). Spatial stimulus-response (S-R) compatibility was manipulated in all conditions. Stimulus degradation and S-R compatibility interacted underadditively, but only in blocked presentations. Both interpretations of underadditive effects were supported. Eye-movement registrations provided additional support for the alternative routes model.

The additive factors method (Sternberg, 1969, 1998, 2001) of analyzing choice reaction times has proved a useful tool for the inference of independent processing stages. The logic underlying this method involves two assumptions. First, it is assumed that information processing consists of a succession of stages (seriality assumption), and, second, it is assumed that a given stage produces a discrete output which is independent of the duration of the stage and is constant across conditions (discreteness assumption). This conception of a stage leads to several implications regarding the relations between the durations of stages and experimental manipulations. First, total RT is the sum of the stage durations. Second, if two different experimental manipulations affect two different stages, they should produce additive effects on RT. Finally, if two task variables affect some stage in common, their effects are expected to interact.

The additive factor method has been criticized concerning the biological plausibility of serial stages (but see Miller, 1988, for an effective reply)

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[2]Please send correspondence to M. van der Schoot, Department of Special Education, Van der Boechorststraat 1, 1081 BT Amsterdam, The Netherlands or e-mail (M.van.der.Schoot@psy.vu.nl).

and, more importantly, concerning its assumptions. The assumptions of discreteness and successiveness have been challenged by the cascade model (McClelland, 1979) and the continuous flow model (Eriksen & Schultz, 1979). In these models, processing in a next stage can start before processing in a previous stage has ended, which makes the inference of the stage structure from additive or interactive effects on RT problematic (McClelland, 1979). On the other hand, extensions of the logic of additive factors, involving tests of the robustness of additive-factor effects under the influence of a third factor (Sanders, 1990, 1998; Sternberg, 1998), tests of additivity of variances, which should hold when stage durations are stochastically independent (Roberts & Sternberg, 1993) and tests of additivity of log-accuracy measures (Schweickert, 1985), have generally been supportive for the linear stage structure. Also, specific tests of the assumption of discrete-stage output have shown that the linear stage structure is viable within a broad range of boundary conditions (Miller, 1987; Meyer, Irwin, Osman, & Kounios, 1988). Further, even if one accepts the possibility that information is transmitted continuously between a pair of stages in a larger sequence of other stages that transmit discretely, additive factor method would still have some utility: one could define a 'superstage' whose overall input and output is transmitted discretely (Miller, 1988). Similar suggestions have been made by Sternberg (1969, 1998) and Sanders (1980): 'overlapping stages' would mean that sets of processes overlap, which together may constitute a single larger stage.

The possibility of temporal overlap between stages has also been considered by Stanovich and Pachella (1977). They proposed that models postulating a temporal overlap of stages are better able to account for underadditive interactions between variables than strictly serial stage models. An interaction of factors is called underadditive if the effect of combined increases in factor level is less than the sum of effects of separate increases. Stanovich and Pachella argued that in difficult task conditions, information can be sent from one stage to the next before processing in the first stage has been completed. Upon completion, the remaining information would also be passed on, but in the meantime the next stage has already processed some information. This would lead to a reduction in total RT that becomes apparent in an underadditive interaction. A similar relation between temporal overlap and underadditivity is proposed by Egeth and Dagenbach (1991), but see Schweickert and Townsend (1989) for underadditive effects arising in more complex 'directed acyclic network'-models.

The conclusions are that the additive factor method has some utility as long as there is at least one point in information processing where transmission is discrete (Miller, 1988), and that underadditive interactions can be used as a tool for detecting temporal overlap of stages.

The concept of temporal overlap between stages is also found in Miller's

Asynchronous Discrete Coding model (1982). Miller showed that clearly separable dimensions of a single stimulus (cf. Garner, 1970) can be processed at the same time. In the present experiment, two task variables were selected to affect the processing of two separable stimulus dimensions, identity and location (see also Ungerleider & Mishkin, 1982). Stimulus degradation was manipulated to affect the detection of the identity of a stimulus (during the stimulus evaluation stage), whereas spatial stimulus–response (S–R) compatibility was manipulated to affect the rate at which location information can be used to select the correct hand (during the response selection stage). Importantly, the identity dimension was mapped on fingers, and the location dimension was mapped on hands. On the basis of earlier findings with studies using separable stimulus dimensions (Miller, 1982, 1987; Osman, Bashore, Coles, Donchin, & Meyer, 1992), we conjectured that information on the location dimension can be transmitted to the response-selection stage before processing of the identity information is completed. The reason for this is that the location information can be used to start partial selection of the response with respect to the hand.

Miller (1982) found that stimulus degradation and S–R compatibility interacted underadditively; that is, the slowing effect of degradation was reduced in case of an incompatible S–R relation. He ascribed this effect to parallel processing in the stimulus evaluation and response-selection stages that were affected by these variables. When the S–R relation was incompatible, the selection of the response hand took longer, and a larger part of the processing of the (degraded) identity information could be done meanwhile. The first aim of this study was to replicate Miller's finding of an underadditive interaction between stimulus degradation and S–R compatibility. It should be stressed that the interaction between stimulus degradation and S–R compatibility is predicted to be underadditive only in case of an above-described mapping of separable stimulus dimensions on response categories. Otherwise we would have predicted these two variables to show the well-established additive effect on RT (Sanders, 1980; Van der Molen, Bashore, Halliday, & Callaway, 1991).

The second aim of this study was to examine whether the expression of parallel processing in RT patterns may be masked when the levels of the independent variable are presented in a mixed design rather than in a blocked design. In a blocked design the same level of an independent variable occurs on all trials of the same block, whereas in a mixed design, these levels vary within a block of trials. Studies in which the independent variable was presented in both a blocked and a mixed design have generally shown an underadditive interaction between design type (blocked or mixed) and the independent variable under examination (see Los, 1996, for a review). For instance, Van Duren and Sanders (1988) manipulated stimulus degradation in conditions of blocked and mixed presentation. A pronounced underadditive interaction was found between design type and stimulus degradation (see also Coles, Gratton, Bashore, Eriksen, & Donchin, 1985): a strong effect of stimulus degradation in the blocked design was almost gone in the mixed design. To account for this effect Van Duren and Sanders (1988) suggested that the stage of encoding contains two alternative processing routes, one of which has an additional subprocess that is needed in the case of suboptimal conditions. This extra subprocess may be concerned with separating relevant from irrelevant features when a stimulus is degraded. When only intact signals are presented, a route can be taken that does not involve the subprocess. Van Duren and Sanders proposed that in a mixed condition, signals are always sent along the more elaborate route because subjects are not aware of the stimulus quality in the forthcoming trial: presetting the optimal process is hindered by 'event uncertainty'. This means that in a mixed condition intact signals will also pass through the extra analysis, which adds extra processing time, although less than when the signal is degraded. Alternative explanations for this and related findings have also been proposed (e.g., Los, 1996, 1999a, 1999b; Lupker, Brown, & Colombo, 1997), but all explanations assume that processing the "fast" level of an independent variable, i.e., of intact stimuli in the Van Duren and Sanders study (1988), is somehow less efficient in a mixed design than in a blocked design.

In the present study, we first evaluated the (underadditive) relation between stimulus degradation and S–R compatibility. Then, we assessed whether this relation was modulated by design type. It was predicted that in mixed conditions the difference in the stimulus evaluation stage duration between intact and degraded stimuli will be smaller than in blocked conditions, and that this will affect RT more in compatible than in incompatible conditions. Therefore, in mixed conditions, the difference in 'degraded minus intact RT' between compatible and incompatible conditions will be smaller than in blocked conditions. This three-way interaction may be stated differently: in incompatible conditions the difference in 'degraded minus intact RT' between blocked and mixed conditions will be smaller than in the compatible conditions.

Finally, we measured saccadic eye movements during task execution by means of an electrooculogram (EOG) registration. One reason for recording the horizontal EOG was to check whether subjects were fixating a centrally presented fixation cross at the start of the trial. Furthermore, the EOG registration enabled us to observe whether subjects made saccades upon the presentation of the digit, and, if so, whether the amplitude of the saccade depended on the experimental conditions. In particular, degraded stimuli may require more foveal analysis than intact digits. Therefore, the third aim of this study was to explore whether the different processing routes proposed by Van Duren and Sanders (1988) may be reflected by distinct patterns of eye-movements.

METHOD

Subjects

Eighteen right-handed male students (ages between 18 and 30 years) at the University of Amsterdam served as subjects. They received course credits for participation. All were healthy and reported normal or corrected-to-normal vision.

Task and Stimuli

The subjects sat alone in a dimly lit room. Stimuli were presented black-on-white for 400 msec. on a VGA screen at a distance of 80 cm. The screen was linked to a Macintosh Plus ED computer that was triggered by a PC-AT (Cremer, Van der Schaaf, & Verheyden, 1991). On each trial the subjects had to respond to intact or degraded versions of the digit '2' or '5' by pressing one of four buttons in front of them. The task was designed to let stimulus location determine the response hand, and stimulus identity determine the particular finger of the hand. The '2' was assigned to the middle finger of the left hand and the index finger of the right hand, and the '5' was assigned to the index finger of the left hand and the middle finger of the right hand. Stimuli were presented at a distance of 32 mm from the fixation cross, either on the left, or on the right, subtending a visual angle of 2.3°, given a viewing distance of 80 cm. In Compatible blocks a stimulus on the left indicated a response with the left hand, and a stimulus on the right indicated a response with the right hand. In Incompatible blocks this mapping was reversed. A digit consisted of a dot pattern surrounded by a rectangular frame consisting of identical dots. Opposite to the side of the stimulus, an empty frame was presented. The size of the frame was 23 mm horizontally and 29 mm vertically with a distance of 80 cm to the subject. Digits were degraded by moving 12 dots from the frame to random positions in the field within the frame not occupied by dots of the digit. To prevent utilization of specific cues there were seven degraded versions of each digit.

Design and Procedure

Each subject carried out four blocks of trials, corresponding to two levels of Stimulus Quality and two levels of S–R Compatibility, both of which were varied between blocks. In an additional two blocks (one Compatible, one Incompatible), intact and degraded stimuli were mixed. In all, the within-subjects design embodied three factors [Stimulus Degradation, S–R Compatibility, and Design Type (Blocked vs Mixed presentation of intact and degraded stimuli)] with two levels each. Each block consisted of 112 trials. The order of blocks was counterbalanced across subjects. Prior to each block, subjects were informed about its nature. The interstimulus-interval between stimuli occurring on subsequent trials was 3020 msec.

Before the main experiment, subjects were trained in blocks of 56 trials, doing each type of block at least once and more often if errors exceeded 10%. Subjects were instructed to respond as quickly as possible, without making too many errors. Feedback of mean RT and errors was given after each block, and subjects were stressed to be (more) regular in their performance if the standard deviation exceeded 15% of the mean RT in that block (see Sanders, 1980).

Physiological Recording

Vertical and horizontal EOG were recorded bipolarly with tin cup electrodes from above and below the right eye and just lateral to the outer canthus of each eye. The voltages were digitized at 100 Hz for 1280 msec., starting 200 msec. before the onset of the stimulus.

Data Analysis

For each subject and experimental condition the first two warming-up trials, incorrect responses, and trials with an RT that deviated more than 2.5 from the mean were excluded from the data. On the horizontal EOG-lead, the amplitude was derived from all samples in the area 0- to 800-msec. poststimulus. An analysis of variance was carried out on the amplitudes with Design Type, S–R Compatibility, and Stimulus Degradation as repeated measures. Univariate F tests were conducted by the program DAR (Kenemans, 1991).

Results

Reaction Time

Fig. 1 displays mean RT as a function of the experimental conditions. RTs were slower for Degraded than for Intact stimuli, slower in Incompatible S–R than for Compatible S–R relations, and also slower when Intact and Degraded stimuli were Mixed rather than Blocked (main effects of Stimulus Degradation, S–R Compatibility, and Design Type: $F_{1,17}=97.0$, $p<.001$; $F_{1,17}=50.1$, $p<.001$; and $F_{1,17}=15.7$, $p<.001$, respectively). The only significant interaction was between Stimulus Degradation, S–R Compatibility, and Design Type ($F_{1,17}=7.7$, $p<.05$). Fig. 1 suggests that the following pattern of effects describes this three-way interaction: effects of S–R Compatibility appeared to be reduced when stimuli were Degraded, but only if Intact and Degraded stimuli were presented in the Blocked condition. To test this suggestion in a direct manner, a number of *post hoc* analyses of variance were carried out. Separate analyses of variance for Mixed and Blocked levels of Degradation indicated that the interaction between Stimulus Degradation and S–R Compatibility was significant in Blocked conditions ($F_{1,17}=8.2$, $p<.05$), but not in Mixed conditions ($F_{1,17}=0.9$, $p=.35$). Two additional separate analyses of variance for S–R-Compatible and S–R-Incompatible blocks indicated that the interaction between Design Type and Stimulus Degradation was significant in S–R-Compatible blocks ($F_{1,17}=10.7$, $p<.01$) but not in S–R-Incompatible blocks ($F_{1,17}=1.2$, ns).

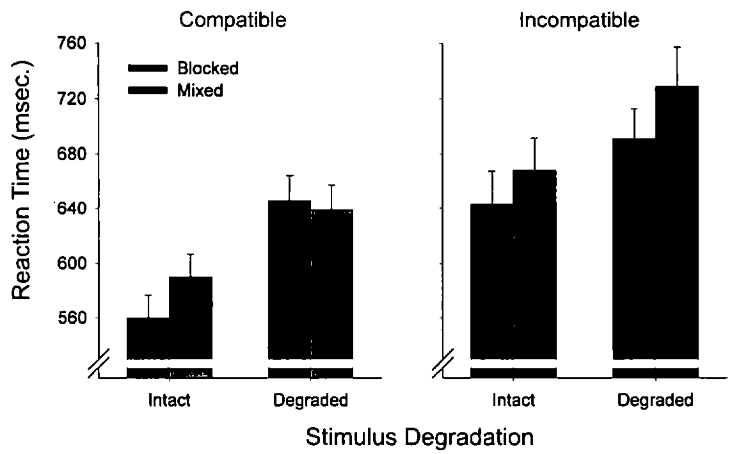

FIG. 1. Mean reaction time (+SE) as a function of stimulus degradation (intact or degraded), S–R compatibility (compatible or incompatible), and design type (blocked or mixed)

Errors

More errors were made when stimuli were Degraded rather than Intact and when the S–R relation was Incompatible rather than Compatible ($F_{1,17}=9.7$, $p<.01$, and $F_{1,17}=4.7$, $p<.05$, respectively). The associated percentages of errors (averaged across blocked/mixed presentation) were for Intact/Compatible 1.3%, for Degraded/Compatible 2.2%, for Intact/Incompatible 2.0%, and for Degraded/Incompatible 2.9%. The percentage of omission errors was small (<0.14%) in every condition.

Horizontal Eye Movements

Fig. 2 shows the grand-average event-related potentials obtained at the horizontal EOG-electrodes in all conditions. It can be seen that the lateral presentation of a stimulus triggered an eye movement in the direction of the stimulated visual hemifield at a latency of about 180 msec. Further, this lateral eye movement was larger for Degraded than for Intact stimuli, especially in Blocked conditions; that is, the figure suggests an underadditive interaction between effects of Stimulus Degradation and Design Type on the average amplitude of eye movements. Analyses of variance on the amplitude of

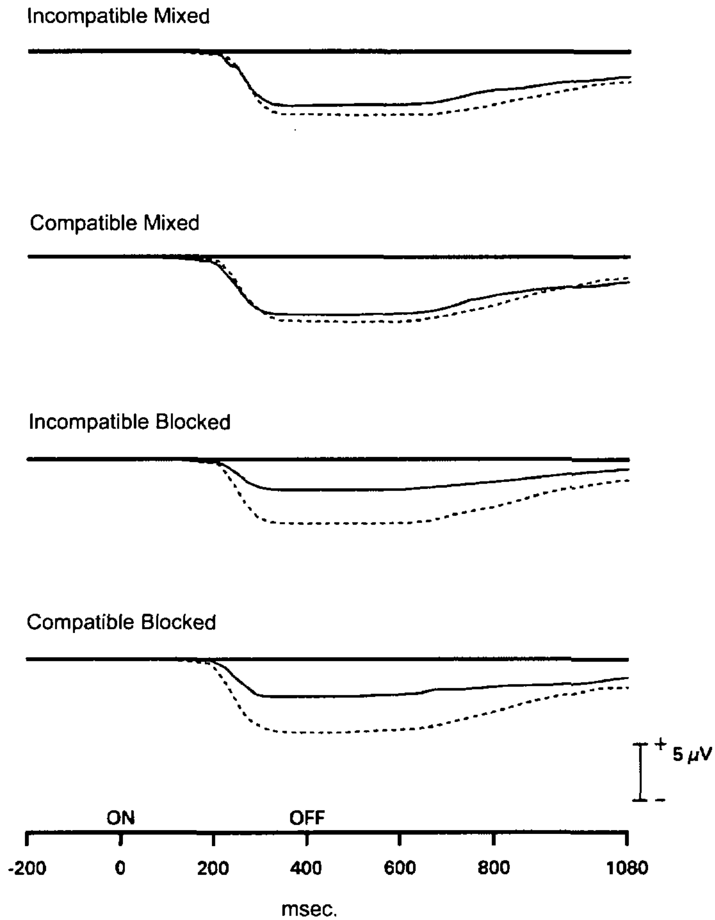

FIG. 2. Grand-average event-related potentials derived from the horizontal electrooculogram as a function of stimulus degradation [intact (——) or degraded (– – – –)], S–R compatibility (compatible or incompatible), and design type (blocked or mixed)

horizontal EOG at each consecutive time point supported this: main effects of both Stimulus Degradation and Design Type were significant at each time point from 200 msec. onward ($F_{1,17}<65.7$, $p<.05$ and $F_{1,17}<7.5$, $p<.05$, respectively). The interaction between these factors was significant at each time point from 190 msec. onward ($F_{1,17}<35.6$, $p<.005$).

Discussion

We sought to test two different but complementary accounts of the appearance of underadditive interactions in experiments employing factorial designs. One account (Stanovich & Pachella, 1977) is in terms of temporal overlap between stages whose independence was presumed on the basis of the concept of asynchronous discrete coding (Miller, 1982). The other account proposes that mixing conditions within blocks leads to suboptimal processing in the easier task conditions (Van Duren & Sanders, 1988).

Therefore, the task variables stimulus degradation, S–R compatibility, and design type were combined in such a manner that the underadditive interaction between two of them could be studied as a function of the third. The results indicated that both underadditive interactions were present. In blocked conditions, there was an underadditive interaction between S–R compatibility and stimulus degradation, and in S–R-compatible conditions, there was an underadditive relation between stimulus degradation and design type. Moreover, the second-order interaction that was expected after combining the principles behind both RT-interactions was also obtained: the subadditive interaction between stimulus degradation and S–R compatibility was only present if the levels of stimulus degradation were presented in separate blocks, presumably reflecting the specific influences of these factors on the overlapping and mutually independent stages of stimulus evaluation and response selection. In mixed blocks, the relation between stimulus degradation and S–R compatibility was additive. This result indicates that the extent to which parallel processing is expressed in underadditivity is affected by design type.

The pattern of effects on the mean RTs in the eight experimental conditions can be understood in terms of the 'alternative-routes model' (Van Duren & Sanders, 1988) and the Asynchronous Discrete Coding model (Miller, 1982). Strictly, however, the postulation of two overlapping stages affected by stimulus degradation and S–R compatibility cannot completely explain the present data. Namely, a basic temporal overlap model would predict that when the slowest stage reaches its longer duration, the duration of the other stage would be irrelevant to RT. Yet, an analysis of selected *post hoc* contrasts of our results indicated that stimulus degradation still had a significant effect on RT in the incompatible condition (blocked design: $F_{1,17} = 21.0$, $p < .001$; mixed design: $F_{1,17} = 49.9$, $p < .001$), and that S–R compatibility still had a significant effect in the degraded condition (blocked design: $F_{1,17} = 28.7$, $p < .001$, mixed design: $F_{1,17} = 22.8$, $p < .001$). Possibly, this discrepancy may be the result of random variability in stage durations.[3] If this variability is sufficient, the duration of the shorter (on average) process will exceed the duration of the longer (on average) process on a certain proportion of trials. This proportion will be larger as the stage duration of the shorter process increases as a result of the associated task manipulation. As a result, the task manipulation of the shorter stage will still have an effect at the difficult level

[3]This possibility was suggested to us by Allen Osman.

of the task associated with the longer stage. This may explain the effect of stimulus degradation for incompatible trials and the effect of S–R compatibility for degraded signals.

The effects on the amplitude of horizontal eye movements toward the stimulus displayed an interaction similar to the underadditive interaction between stimulus degradation and design type that was observed for RT. When intact and degraded stimuli were presented in separate blocks of trials, the amplitude of eye movements was significantly larger for degraded than for intact stimuli. If intact and degraded stimuli were mixed, however, horizontal eye movements towards intact stimuli increased to a level close to the level obtained for degraded stimuli. Interestingly, these effects mirror the effects on RT and may be produced by the same mechanism that was proposed for the interpretation of the pattern of effects for RT. Van Duren and Sanders (1988) proposed that the underadditive interaction between stimulus degradation and design type is produced by a strategical choice for a processing route that is suboptimal for intact, but not degraded, stimuli in mixed designs. In blocked designs, a faster processing route might be employed for intact stimuli because the subject has advance knowledge about the quality of the stimulus. The pattern of effects for eye movements may be accounted for by a similar mechanism. It is well possible that intact stimuli can be identified from the corner of the eye. Therefore, in a block of trials that contains only intact stimuli, stimuli may be identified without making the large eye movements that are associated with bringing the stimulus in the fovea. For the identification of degraded stimuli, however, foveation may be required. If intact and degraded stimuli are randomly mixed within a block, there is no advance knowledge about the quality of the stimulus, and subjects will adhere to a 'fail-safe' strategy that enables them to identify both intact and degraded stimuli. In this strategy, all stimuli are foveated by making relatively large eye movements. Thus, the pattern of eye movements in the present task may reflect the strategical mechanism proposed by Van Duren and Sanders (1988) and replicated. During saccades, visual information pressing is known to be blocked (Sanders & Houtmans, 1985), which provides for a possible mechanism responsible for the costs of mixing in intact conditions.

It should be recognized that, in contrast to the RT results, the interaction between stimulus degradation and design type did not vary as a function of S–R compatibility for the amplitude of horizontal eye movements. A plausible explanation for this dissociation is that all processes up till and including a saccadic eye movement reflect perceptual processing only (Van Duren & Sanders, 1992; see Sanders, 1998, for a review), whereas RT reflects central and motor processes in addition. Therefore, the influence of S–R-compatibility is expected to be limited to the RT data.

In conclusion, not only the RT results of this experiment suggest that the stage of feature extraction contains at least two parallel processes, the alternative-routes model (Van Duren & Sanders, 1988) also receives support by the electrophysiological measurement of horizontal eye-movements.

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